# Numerical and Experimental Investigation of Meteoroid Ablation

Eric C. Stern[1], Y-K. Chen[1], Susan White[1], and Dinesh K. Prabhu[2]

eric.c.stern@nasa.gov [1]NASA Ames Research Center, Moffett Field, CA [2]Analytical Mechanics Associates, Inc., Moffett Field, CA

**Objective:** In this work we give an overview on early efforts toward understanding and modeling the process of meteoroid ablation, both through numerical simulation and ground-based experiments at a high-powered laser facility. Numerical modeling efforts focus on applying methodologies developed for modeling ablative spacecraft thermal protection system (TPS) material to the problem of meteoroid ablation. Experimental effort focuses on providing validation data for numerical modeling, as well as providing insight into the fundamental mechanisms of meteoroid ablation.

## Classical Physical Theory of Meteors

The ablation process for meteor entry is typically modeled using the simple mass loss relation from classical meteor physics [1].

$$\frac{dM}{dt} = -\Lambda \frac{S\rho v^3}{2Q}$$

This equation states that the rate of mass loss for a meteoroid is proportional to the heat transfer coefficient ($\Lambda$), and inversely proportional to the so-called heat of ablation, $Q$. The heat of ablation is typically taken to be the sum of heats required to vaporize the material, as in:

$$Q = h_1 + h_f + h_2 + h_v$$

where the terms on the right hand side are: heat required to raise the temperature of the material to its melting point, heat of fusion, heat required to raise the melt temperature to its boiling point, and heat of vaporization. This sum yields the canonical value for heat of ablation of 8.08 MJ/kg for *stony* meteoroids, and 8.26 MJ/kg for *iron* meteoroids.

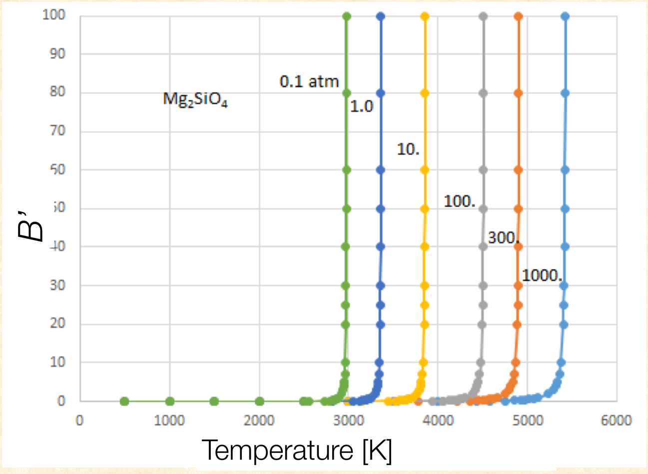
## Equilibrium Ablation Model

One of the aims of this project is to explore the possibility of using the material thermal response modeling approach used in the design of thermal protection systems of entry vehicles to meteor entries as well. We begin with a simplified surface energy balance (SEB) for meteoroid entry:

$$\underbrace{C_H(H_r - h_w)}_{\text{convective heating}} - \underbrace{\dot{m}\Delta h_v}_{\text{heat loss due to vaporization}} + \underbrace{\alpha q_r}_{\text{absorbed radiation}} - \underbrace{\sigma\epsilon(T_w^4 - T_\infty^4)}_{\text{re-radiated heat}} - \underbrace{q_{cond}}_{\text{heat lost due to conduction into body}} = 0$$

The first and third terms are typically provided from aerothermal CFD predictions. If chemical equilibrium may be assumed near the surface, then an equilibrium solver may be used to determine the mass loss rate. Typically the parameter B', which is defines as:

$$\dot{m} = C_M B'_s$$




*Plot of B' vs. Temperature at various surface pressures for the olivine end-member forsterite which is prevalent in stony meteorites.*

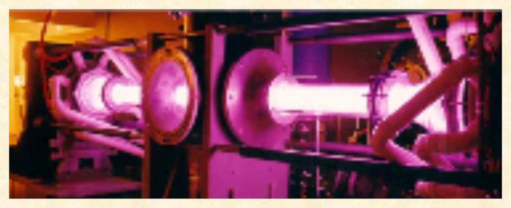
is computed for a range of temperatures and pressures (*right figure*) before the simulation, and then used to quickly compute the mass loss rate.

## Ground Testing Approach

In meteoroid entry modeling — as in spacecraft modeling — it is a challenge to replicate the extreme environment found in hyper-velocity atmospheric entry in order to validate models for ablation. Furthermore, it has been shown [2] that heating for bodies of interest to PD (>10m) is dominated by radiation from the shock-heated gas, and can exceed 100 kW/cm$^2$. Therefore, in order to in-part emulate this environment, we have undertaken a laser-heating campaign using the Laser Hardened Materials Evaluation Laboratory (LHMEL).

### LHMEL

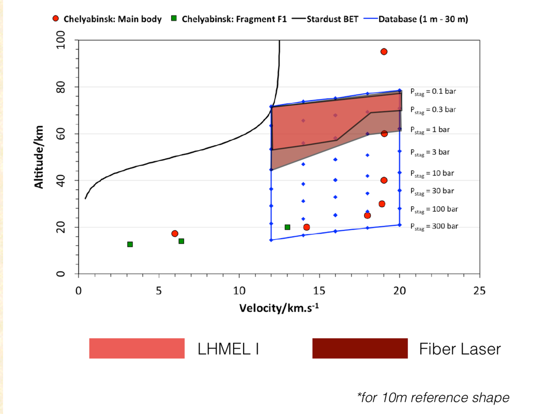
The LHMEL facility is comprised of four different continuous wave (CW) laser assets: a 10kW and a 100kW $CO_2$ laser (10.6 micron), as well as a 10 and 20kW fiber laser (1.07 micron)



*The 10kW LHMEL I $CO_2$ laser in use*

### Proposed Exploratory Test

We have performed a preliminary campaign to asses the utility and feasibility of laser heating for studying the underlying phenomena in meteoroid ablation. This exploratory campaign utilizes the 20kW fiber laser to test samples of meteoritic material (*below*), as well as terrestrial rocks




*Available LHMEL conditions (heating and pressure) for exploratory test, with the Chelyabinsk bolide and Stardust entry vehicle shown for reference.*

*Fragments of the Tamdakht (H5) chondrite which fell in 2008*

*Fragment of the Sikhote-Alin iron meteorite*

## Experimental Set-up

An image of a sample in the sample holder can be seen below. Some important features of experimental set-up are as follows:

- A flow of $N_2$ at 1 m/s is used to prevent blockage of beam by ablation vapor
- A fraction of the beam is reflected to a detector for in-situ measurement of spot size and irradiance
- 3-color pyrometer gives estimate of surface temperature during the test

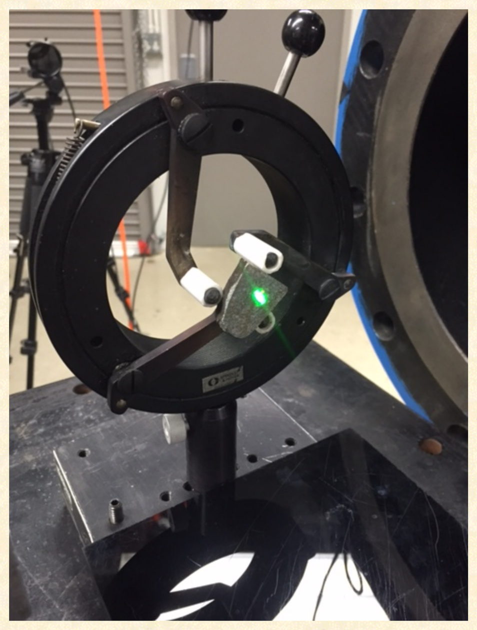
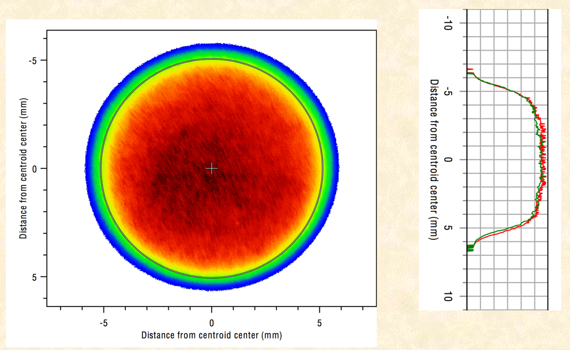


*Image of the sample holder (chondrite sample pictured), along with the alignment beam*

| Material | Heat Flux (kW/cm2) |
|---|---|
| Tamdakht (H5 Chondrite) | 4.5, 9.0, 14.9 |
| Sikhote-Alin (IIB Iron Meteorite) | 14.9 |
| Basalt | 4.5, 9.0, 14.9 |
| Quartz | 14.9 |
| Fused Silica | 14.9 |

*Table of materials and conditions for the exploratory campaign*

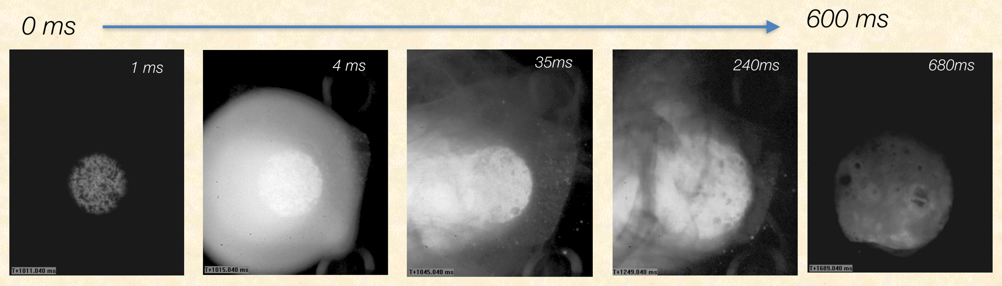



*In-situ beam profile output from a 10kW exposure. Sharp lined circle shows nominal 1cm diameter spot. Contours show relative radiative intensity*

## Preliminary Observations from Exploratory Campaign

The exploratory test campaign at LHMEL was completed on June 4. Analysis of the data is in its early stages, however some preliminary observations have been made:

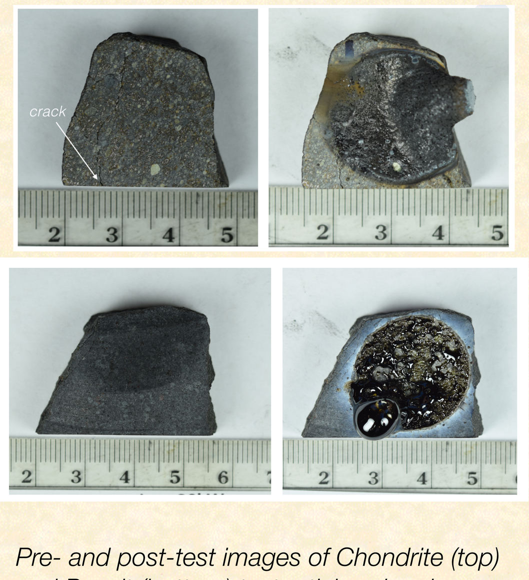
### High Speed Video




*Frames from high-speed video of one of the chondrite samples exposed at ~20kW/cm2*

- High speed video is yielding insight into the fundamental mechanisms of meteoroid ablation
- Vaporization appears to dominate in chondrite ablation; spraying of molten drops more prevalent in basalt samples

### Fusion Crust Characteristics



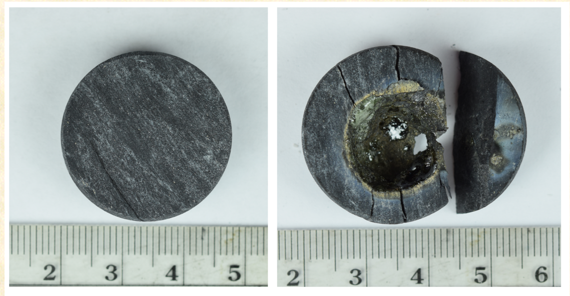
*Pre- and post-test images of Chondrite (top) and Basalt (bottom) test articles showing difference in fusion crust characteristic*

- Residual melt layers (fusion crusts) show distinctly different characteristics between materials.
  - Terrestrial samples display glassy web-like fusion crust, while chondrites show smoother matte crust
- Fusion crust generated by experiments (particularly at higher power) closely resembles that from actual entry environment for chondrite samples

*Comparison of experimental (left) and entry (right) fusion crusts*

### Fracture of Samples

- None of the meteoric samples tested displayed any noticeable thermally induced fracture, though several had cracks to begin with
- Several of the basalt samples showed cracking or wide-spread fracture due to thermal stress



*Pre- and post-test image of a Basalt sample which experienced significant fracture due to thermal stress. This sample was subjected to a 5kW/cm2 flux*

**References:**
[1] Öpik, *Physics of Meteor Flight in the Atmosphere*, 1958
[2] Prabhu et al., *IAA Planetary Defense Conference*, 2015

**Acknowledgments:**
This work is a part of the Planetary Defense Integrated Product Team funded by Lindley Johnson at the NASA NEO program office. The authors would like to gratefully acknowledge Greg Gonzales and Michael Gusman of Analytical Mechanics Associates for their invaluable assistance in processing the experiment samples. Additional thanks to Dan Seibert and Braden Childers at the LHMEL facility for their technical expertise in conducting the laser tests.